Tailored Fiber Placement—Mechanical Properties and Applications

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ABSTRACT: Tailored Fiber Placement (TFP) is a new automated textile process for the production of reinforcing structures. This process allows the consistent transfer of calculated locally optimum fiber quantities and orientations into fiber preforms. The mechanical properties achieved with TFP reinforced carbon fiber/epoxy and glass fiber/epoxy are compared with tape and fabric reinforced composites. Generally, static mechanical properties of TFP-laminates are better than fabric laminates and close to tapes. However, the ultimate compression strength of carbon/epoxy TFP is lower than comparable tape composites. Fatigue behaviour of a cross-ply carbon/epoxy TFP is compared with a fabric reinforced laminate. The advantages and possibilities of TFP are demonstrated by means of typical applications like bicycle components.

KEY WORDS: tailored fiber placement, preform, composite material, mechanical property, application.

1. INTRODUCTION

IN COMMON FIBER reinforced composite components the anisotropic properties are usually not being fully exploited. Figure 1 shows the importance of identical fiber directions and load directions [1]. If the angle between the fiber and the load direction differs by only 10 degrees then the strength is reduced to about 20% of the maximum.

This makes clear that through the maximum exploitation of the fibers, very light weight composite structures are possible. Therefore, tailored preforms, fine-tuned for a specific part, promise a great advantage in making efficient composite components. Prerequisites for tailoring the fiber directions and fiber amounts in a composite component are: exact knowledge of the load cases, small number of load cases, a production technique to convert the desired layup into a real layup, and can the tex-

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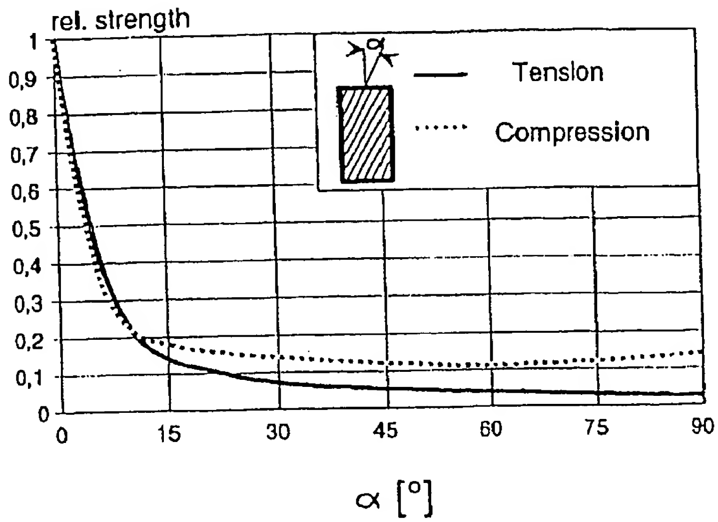

Figure 1. Relative strength of UD carbon/epoxy composite depends on the angle between the load and the fiber direction (by Tsai).

tile structures be processed to composite components.

Tailored Fiber Placement (TFP), an invention of the Institute for Polymer Research Dresden, fits these requirements. An early approach of this concept was presented by Rothe [2]. With TFP it is possible to produce fiber preforms with stress field aligned fiber orientations. The process is based on the well-known embroidery technique used for decorating fabrics. Figure 2 shows the principle of the process.

By stitching with a needle yarn a roving is fixed on a base material. In between the stitches the base material is moved in the X,Y-direction. The roving is fixed with zigzag stitches on either side of the roving. The roving can be made of carbon, glass or other types of fiber. In case of thermoplastics also commingled fibers are possible. The base material can be a fabric or a nonwoven. Suitable is a thin glass fi-

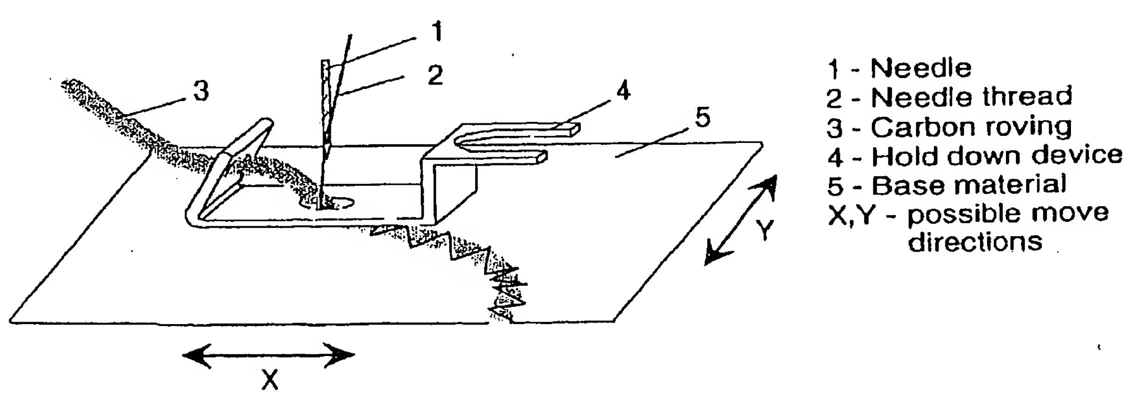

Figure 2. Principle of tailored fiber placement.

ber fabric. In most cases the needle yarn used is a polyester. Typical needle yarn contents in the composite range from 1% to 4% by volume. This is comparable with the yarn contents in warp knitted fabrics. More detailed information about the process is given by Gliesche and Feltin [3,4]. Figure 3 shows one of four TFP-units of the embroidery machine in the Institute of Polymer Research Dresden. The working area of one unit is 700 mm × 700 mm.

The main advantage, compared to common textile technologies, is the ability to arrange reinforcing fibers in every direction of the reinforcing area from an angle of 0° to 360°. Accumulation of fibers is achieved by stitching several times across the same area. In this way the preform is tailored to the stresses in the specific component. Embroidery machines well tried in the textile industry are relatively cheap and need only a minor adaptation for TFP. The highly automated production process allows good reproducibility, and is therefore ideally suited for series production. The near-net shape preforms are made using material from roving spools resulting in almost no fiber waste. With the TFP-technology cost-effective preforms with excellent strength-to-weight characteristics come within reach. Standard production techniques, such as RTM and the vacuum bag resin injection process, can be used to consolidate the preform to a finished product.

The aim of this paper is to demonstrate the advantages and possibilities of TFP. Static mechanical properties and fatigue data of TFP laminates are compared with tape and fabric reinforced composites. Fields of application are demonstrated by means of typical composite parts.

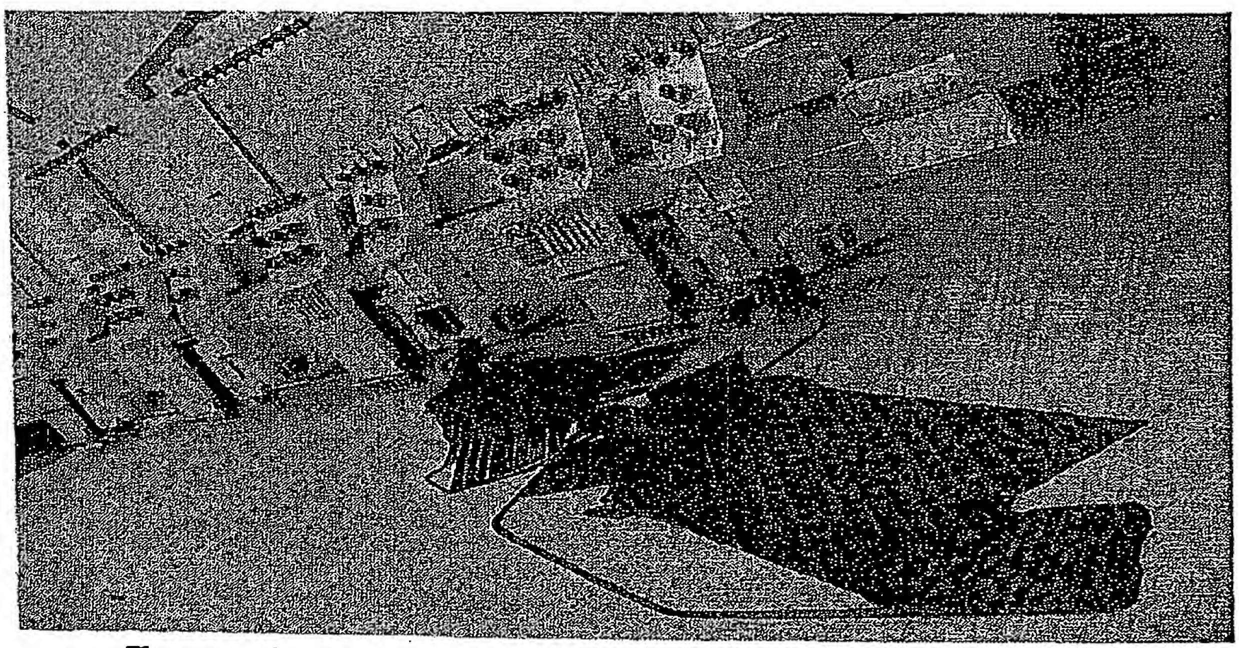

Figure 3. One of four working units of the modified embroidery machine.

2. STATIC MECHANICAL PROPERTIES

2.1 Materials and Specimen Preparation

TFP-preforms were manufactured using a fiber placement machine with four working units. The needle yarn was a polyester. The base material was a thin glass fabric with 100 g/m² areal weight. The preforms were consolidated using the vacuum bag resin injection process. During the consolidation process every preform was covered with a steel plate to create a smooth surface on both specimen sides. Mould temperature during injection was 35°C. The used epoxy resin system Rütapox VE 3966 (Bakelite AG) is a low viscosity RTM-resin. After the resin had wetted out the complete preform the mould temperature was raised to 80°C for one hour for curing. Specimens were cut with a water cooled diamond saw.

2.2 Static Test Results

Mechanical properties of TFP epoxy laminates with continuous glass fiber and carbon fiber are compared with conventionally reinforced laminates. Table 1 shows static test results for unidirectional carbon/epoxy TFP laminates. TFP laminates were tested in tension, compression and in 3-point bending. For comparison prepreg tape values from the literature are included. The values for stress and modulus are also given normalized to a fiber volume content of 55%. The fiber content for TFP refers to the amount of carbon fiber only without the glass base material and polyester needle yarn. The actual fiber content in the fiber layers is higher, typically around 55%, because the base material together with the needle yarn results in a resin rich layer of approximately 0.2 mm thickness.

Table 2 lists static test results for glass/epoxy TFP and tape material. The tensile, compressive and flexural values for ultimate stress and modulus are also given nor-

Table 1. Mechanical properties of unidirectional carbon/epoxy.

Test		Carbon/Epoxy	V_f	S/C.O.V. MPa/%	S* MPa	E/C.O.V. MPa/%	E* GPa
Tension (DIN EN2747)	TFP	Tenax HTA 5331 (12k)/ Rütapox VE3966	0.48	1,438/3.8	1,641	115/0.5	131
Compression (mod. celanese)	TFP	Tenax HTA 5331 (12k)/Rütapox VE3966	0.52	869/3.2	928	—	—
3-P-bending (DIN 53452)	TFP	Tenax HTA 5331 (12k)/Rütapox VE3966	0.52	1,273/3.5	1,347	94/2.3	100
Tension	Tape [5]	T300/#3601	0.60	1,630	1,494	132	121
Compression	Tape [5]	T300/#3601	0.60	1,500	1,375	123	113
3-P-bending	Tape [6]	Tenax HTA/Ep.	0.60	1,990	1,824	131	120

*Normalized to V_f = 0.55; bracketed numbers indicate literature values.

Table 2. Mechanical properties of unidirectional glass/epoxy.

Test		E-Glass/Epoxy	V_f	S/C.O.V. MPa/%	S* MPa	E/C.O.V. GPa/%	E* GPa
Tension	TFP	EC17-1200-G52/D/ Rütapox VE3966	0.52	904/3.0	958	42.0/1.9	44.5
Compression	TFP	EC17-1200-G52/D/ Rütapox VE3966	0.52	797/11.7	848	—	—
3-P-bending	TFP	EC17-1200-G52/D/ Rütapox VE3966	0.52	1,107/3.5	1,173	31.2/2.5	33.1
Tension	Tape [7]	—	0.6	1,000	917	45	41.3
Compression	Tape [8]	—	0.6	704	806	35.9	41.1
3-P-bending	Tape [8]	—	0.6	1,170	1,073	39	35.8

*Normalized to $V_f = 0.55$; bracketed numbers indicate literature values.

malized to a fiber volume content of 55%. The fiber content refers to the glass fiber reinforcement including the glass fiber from the base material.

In real components often fiber reinforcements are needed in more than one direction for instance in two directions as a cross-ply. Table 3 shows mechanical properties for cross-ply carbon laminates. TFP test results of a 7-layer laminate with layup [base material/$(0/90)_3/0$)] are listed together with values from carbon fabric composites from the literature.

2.3 Discussion

The values for UD carbon fiber reinforced TFP only partly reach those from prepreg tape. The tensile strength of 1624 MPa is comparable with tape material. The compressive strength however is significantly lower than tape, which also af-

Table 3. Mechanical properties of 0°/90°-carbon/epoxy.

Test		Carbon/Epoxy	V_f	S/C.O.V. MPa/%	S* MPa	E/C.O.V. MPa/%	E* GPa
Tension	TFP	Tenax HTA 5331 (12k)/ Rütapox VE3966	0.52	824/6.1	875	70.6/2.2	75
Compression	TFP	Tenax HTA 5331 (12k)/ Rütapox VE3966	0.51	548/8.3	586	—	—
3-P-bending	TFP	Tenax HTA 5331 (12k)/ Rütapox VE3966	0.50	808/2.9	855	59.1/0.5	62.8
Tension	Satin 1/5 [9]	C (3k)/MY720	—	597	—	—	—
Compression	Satin 1/5 [9]	C (3k)/MY720	—	542	—	—	—
3-P-bending	Plain weave (200 g/m^2)	Carbon/ Rütapox VE3966	0.52	767/2.4	819	48.6/2.5	51.9

*Normalized to $V_f = 0.55$; bracketed numbers indicate literature values.

fects the flexural strength. The low compressive strength of TFP is explained when looking at the micrograph of Figure 4 showing TFP with a unidirectional layup. From left to right there is a resin rich layer with needle yarn and glass fabric base material followed by roving layers intermitted by bundles of needle yarn. During the built up of the preform the needle stitches into the new and the already placed roving. This stitching process can damage the fibers because single fibers are pushed aside temporarily. Secondly the needle yarn causes a waviness in the laminate. The local fiber orientation is therefore not ideally straight although the global orientation is not affected. The negative influence of fiber waviness on compression strength is well known [10].

The ultimate tensile, compressive and flexural stresses of UD glass fiber TFP are on the same level as those of tape material. The needle stitches during the manufacturing process apparently have no significant influence on the ultimate strength of glass fiber TFP. The glass fibers are more robust than carbon fibers are, due to their isotropic properties. Because of the larger diameter of glass filaments, giving higher flexural fiber stiffness, fiber waviness is not so pronounced as with carbon fiber. Ultimate compressive strength of glass fiber TFP is not affected.

The TFP cross-ply carbon laminate has a significantly higher ultimate tensile strength than the satin weave laminate. The ultimate compressive strength of cross-ply TFP is equivalent to fabric.

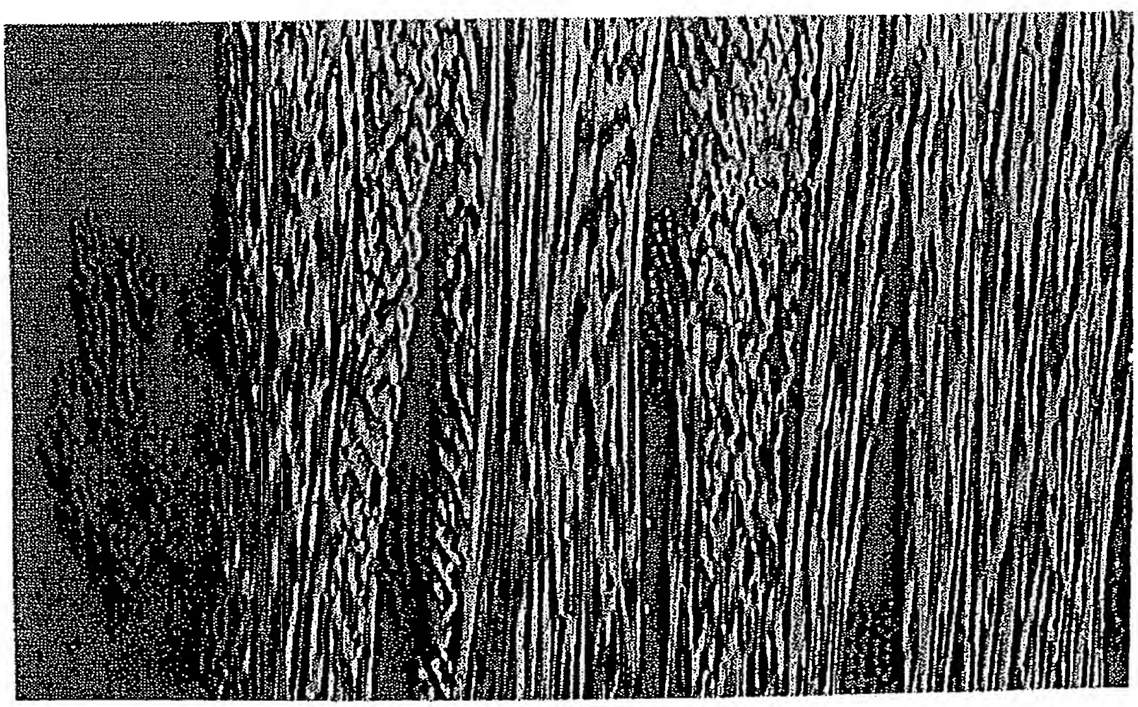

Figure 4. Micrograph of UD carbon/epoxy TFP.

Generally speaking, the static mechanical properties of TFP-laminates reach values better than fabric laminates and close to tapes. The ultimate compressive strength of carbon fiber reinforced TFP however, is significantly lower than corresponding tape laminates. The properties presented above represent the state of the art of TFP. Future work will concentrate on further improving the properties achievable with TFP. Especially compressive strength of carbon reinforced TFP could benefit from the use of thinner needles and needle yarns.

3. FLEXURAL FATIGUE PROPERTIES

Flexural fatigue tests were performed to get a first impression of the fatigue behaviour of cross-ply TFP. For reference a cross-ply plain weave carbon fabric laminate was tested as well. At first quasi-static 3-point bending tests were performed. Table 3 shows the static flexural properties of both laminates. The mean static strengths of both materials were nearly the same, see the readings on the Y-axis in Figure 5. After that fatigue tests were performed using the same test setup. The R-value ($=F_{min}/F_{max}$) was chosen 0.05. The load level for the TFP-laminate ranged from 81 to 89% of the static mean load and for the fabric from 77 to 82%. The results of both the static and the fatigue tests are shown in Figure 5. Comparison of the semi-logarithmic regression lines of TFP and fabric shows that the TFP-line has the flatter slope. This means that the fatigue strength at a given number of cycles to failure is higher for TFP than for plain weave fabric. However, scatter of the TFP-data is higher than for the fabric laminate, possibly caused by the more coarse structure of the TFP.

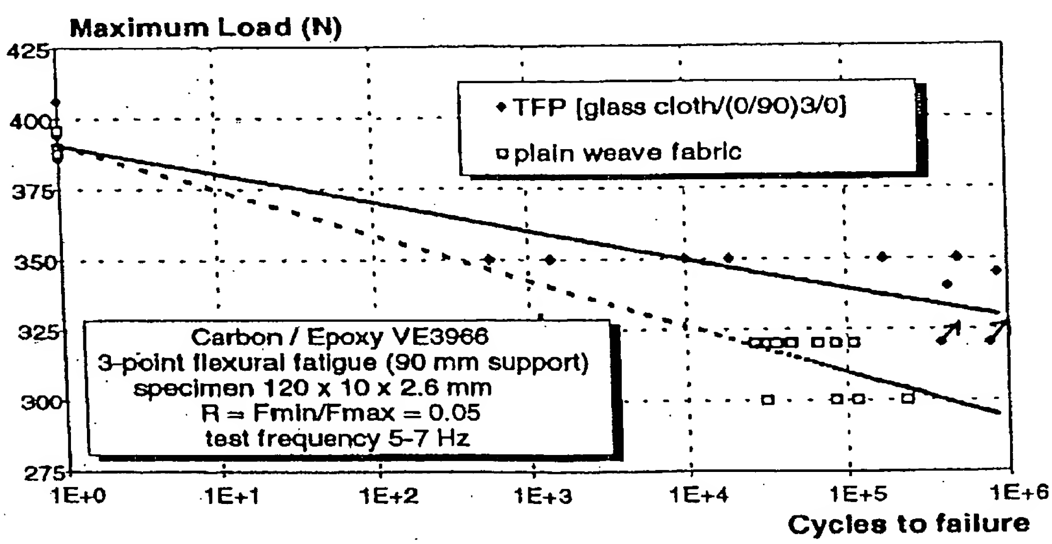

Figure 5. Flexural fatigue of TFP reinforced and plain weave fabric reinforced cross-ply carbon/epoxy.

4. APPLICATIONS

4.1 Bicycle Components

4.1.1 BRAKE BOOSTER

TFP is especially suited for light-weight parts with a complicated stress course. Then its ability to arrange the reinforcing fibers in any direction in the plane in curvilinear format can be exploited. Such a part is a brake booster used to support the brake of a bicycle. This component is mounted at the brake and prevents deformations of the brake shoe holder devices. The pinch forces of the brake shoe holder are introduced in the part via two holes, see Figure 6. This leads to outward pointed loads in the part. Because the brake booster is a curved beam the stress field of this component for the represented load case is easy to determine. The outer and inner areas (flanges) will be loaded in respectively compression and tension and the middle area mainly in shear and compression. Therefore, the fibers in the outer and inner areas are placed in the circumferential orientation and the fibers in the middle at an angle of approximately

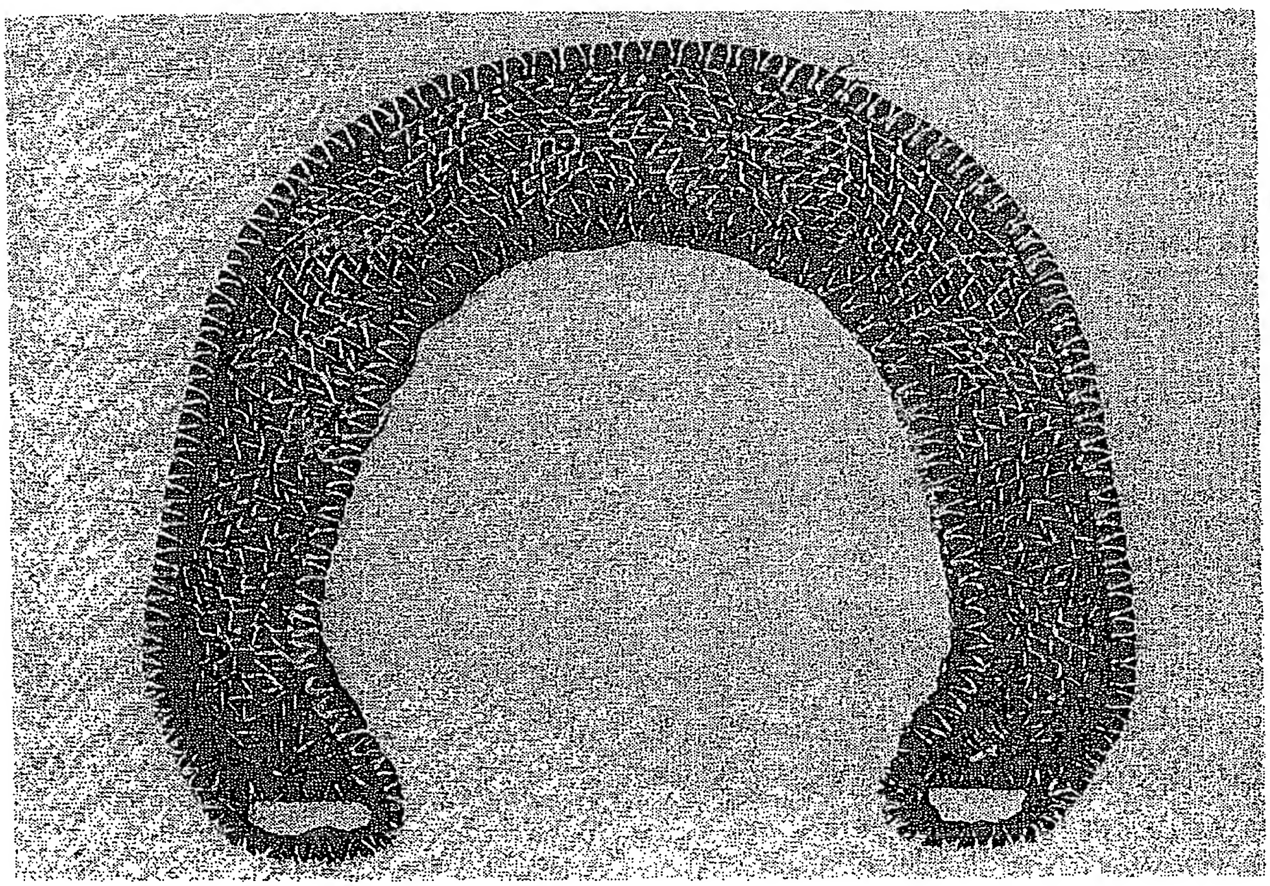

Figure 6. *TFP carbon brake booster preform (real size 130 mm × 135 mm).*

±45°. Figure 6 shows the preform for this brake booster made with a 12K carbon roving. The amount of fibers in the flanges is more than in the middle sheet resulting in a cross-section with varying thickness. An advantage of TFP compared to other textile reinforcements is the near-net shape production. A brake booster preform made of fabrics would be only possible with a lot of fiber waste without reaching the effectiveness of the TFP-Preform. The preform was consolidated using the vacuum bag process. The TFP brake booster was tested together with an aluminium one for reference. The relative stiffness of the aluminium brake booster is 1.8 N/mm/g compared to 6.5 for the composite one. Related to the component mass the carbon brake booster is 3.6 times stiffer than the aluminium reference part.

4.1.2 LINK PLATE

A link plate is used in full suspension bikes and transmits impulses from the back wheel over struts to a spring unit. The principle function and the load case are shown in Figure 7. The main load is the compression load no. 4. The loads are introduced in the part via bolt holes. The fiber preform for this component should reinforce the bolt holes and transfer tension and compression loads directly from hole to hole. This leads to the fiber alignment shown in Figure 8. The UD-reinforcements at the edges of the component transfer tension loads while the UD-reinforcements at the center lines through the bolt holes take over the compression loads. The central area is filled with an unidirectional layup under an angle to the main compression load to support against buckling. The preform mass is 7 g and the finished part transfers a load of over 10 kN determined in an experiment. This carbon preform is small and therefore production time is only about 12 minutes. This means that by using TFP-machines with twelve parallel driven placement units or more an output of one preform per minute becomes feasible.

4.1.3 BICYCLE FRAME

The requirements for a bicycle frame are among other things drive comfort

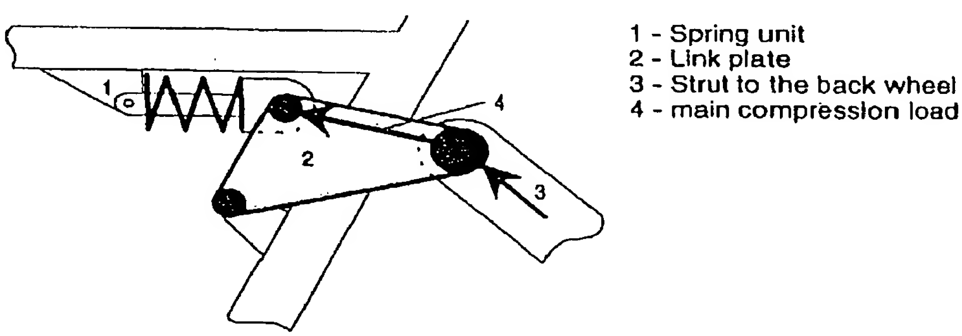

Figure 7. Principle function and load case of the link plate.

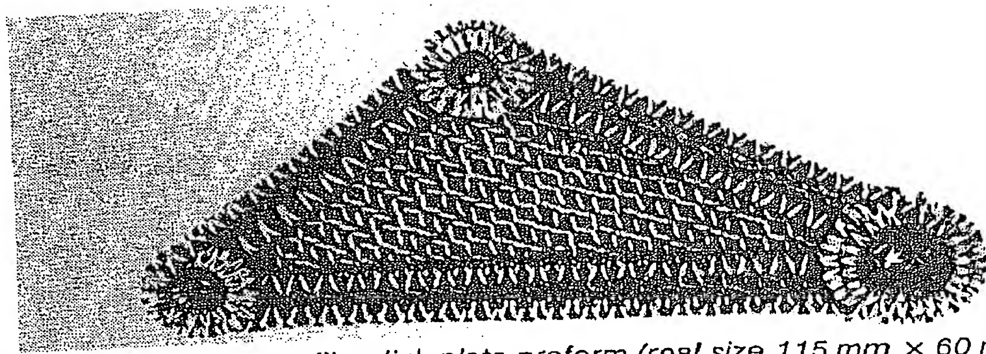

Figure 8. Carbon fiber link plate preform (real size 115 mm × 60 mm).

and minimum production costs. The drive comfort requires a high torsion stiffness in the front part of the frame. At the same time the vertical bending stiffness should not be too high to keep a smooth ride. Additional requirements lead to the layup shown in Figure 9. Locally different fiber amounts and fiber orientations are required. In the center of the frame the complicated design requires an extra inner wall for reasons of stiffness. The TFP-preform tailored for this frame mainly consists of two parts. One preform forms the frame from the steering shaft to the seat. The second preform is wrapped around the first one to form the rear end. The preforms are tailored to the frame not only regarding fiber layup but also concerning size. Less than 1% of the carbon fiber used is wasted. After removal of excess base material the near-net shape preforms can be handled very easily. Figure 3 shows the front preform being manufactured on a modified embroidery machine. Figure 10 shows the finished carbon frame of a piece made with the vacuum bag resin injection process. The frame mass is 1600 g plus metal inserts.

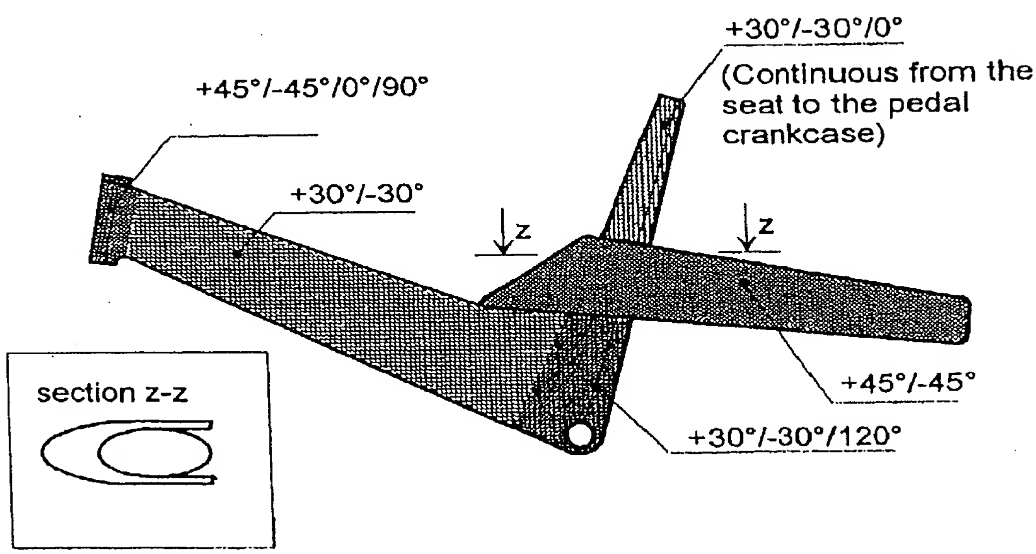

Figure 9. Reinforcing structure of the frame.

Figure 10. Carbon/epoxy bicycle frame (courtesy Sachsen Zweirad GmbH).

4.2 Local Reinforcements

An interesting field of application for TFP is the combination of conventional textile reinforcements with TFP. This combines the design freedom of TFP with the productivity of a surface fabric. Crothers et al. [11] tested such a combination to relieve a stress concentration in a notched composite. An open-hole tension plate and a bearing plate designed for a bolt loaded in double-shear were selected as test components. The base material was a laminate made from a quasi-isotropic multi-axial warp knitted fabric. Both the base material and the TFP reinforcement were of glass fiber and the resin was RTM6 epoxy. Several local reinforcements were tested to relieve the stress concentration. The TFP reinforcements shown in Figure 11 gave the best results. Specific tensile strength could be increased by 45% for the open-hole tension plate and 68% for the bearing plate. Arranging the TFP reinforcement in between the warp knitted fabrics yielded the best results. An extra feature of TFP is that the needle yarn can also be used to reinforce the structure in the third direction there where delaminations are expected.

5. CONCLUSION

Tailored Fiber Placement is a promising technique for the automated manufacturing of tailored preforms for composite components. The preforms are tailored

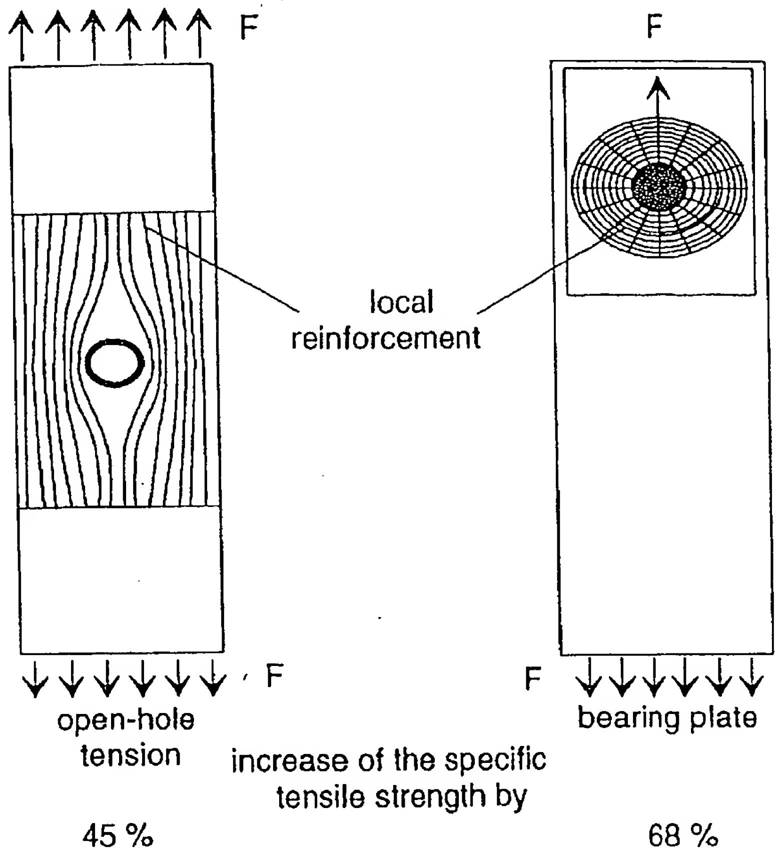

Figure 11. Local reinforcements for an open-hole tension and a bearing plate.

with respect to near-net shape, fiber amount and local fiber orientation resulting in cost-effective and light-weight components. Generally static mechanical properties of TFP-laminates reach values better than fabric laminates and close to tapes. The possibilities of TFP are demonstrated by some typical applications. TFP is especially suited for parts up to 700 mm × 700 mm in size with complex load paths and for locally reinforcing large components. Further investigation is going on to determine in more detail the properties achievable with TFP. Also, a wider use of the technique, e.g., for 3-D reinforcements or preforms for deep drawn parts is under investigation.

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